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PROCEDURES TO CALCULATE RADIOLOGICAL AND TOXICOLOGICAL EXPOSURES FROM AIRBORNE RELEASES OF DEPLETED URANIUM

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Prepared for:

U.S. Army
ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
Dover, New Jersey

Prepared by:

Daniel A. Ensminger
Sharon A. Bucci

THE ANALYTIC SCIENCES CORPORATION
One Jacob Way
Reading, Massachusetts 01867

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PREFACE

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SUMMARY

The 105mm Armor-Piercing, Fin-Stabilized, Discarding Sabot-Tracered (APFSDS-T), Kinetic Energy XM774 and M735A1 cartridges, developed by the U.S. Army Armament Research and Development Command (ARRADCOM), are intended for use in tanks equipped with an M68 gun. These cartridges, both containing a depleted uranium (DU) penetrator, will provide improved penetration effectiveness over the currently fielded M392 and M728 series of armor-piercing, spin-stabilized, discarding sabot rounds and the M735 APFSDS-T cartridge.

A concern of using these munitions is centered on potential radiation and toxicity exposures which may result from scheduled or accidental releases of the DU penetrator to the air as fine particles. Depleted uranium metal is formed as a by-product of the uranium enrichment process, and contains a very small percentage, by weight, of the lighter, faster decaying ^{234}U and ^{235}U isotopes. Thus the activity of DU is much less than that of natural uranium, although chemically both metals have similar properties.

A number of efforts have been conducted within the Army to obtain a clearer understanding of expected radiological and toxicological exposures resulting from airborne dispersions of DU material under given release conditions. Although the fundamental approach is similar in each evaluation, variations in procedures and assumptions impede direct comparison of results and, in general, limit the applicability of the information to the overall question of consequences from airborne releases of DU munitions. Consequently, there is a need to establish uniformity in the methods and assumptions used to determine these exposures.

In this report, the framework for calculating radiation and toxicity exposures is outlined. Section I provides a detailed treatment of the Gaussian diffusion model typically used to simulate the transport of material dispersed into the air from a point-source release. Employing the model for given release conditions, the following concentrations of DU can be determined at various distances downwind of the source: (1) instantaneous, average, or integrated concentration of material in the air and (2) concentration of material deposited on the ground from the passing cloud. Instantaneous (puff) and continuous (plume) release modes are described for both constant and random wind conditions, addressing the requirements, application, and pertinent considerations for the use of each. Also discussed is the isotopic composition of the DU source term, the effect of atmospheric stability on airborne dispersion, general guidelines for model use, and a general treatment for estimating the contribution of resuspended materials to air concentrations.

In Section II, methods and criteria are presented for determining the radiological and toxicological insult from either occupational or general populace exposures to airborne uranium material. Measures of exposure include: whole-body dose, critical-organ dose, radiological concentration of DU in air -- for evaluating radiation insult, and concentration of soluble DU in air -- for assessing chemical toxicity burden. T'e effects of solubility on radiological exposures are discussed. All measures reflect the internal buildup of uranium within the body or its organs and, where applicable, external irradiation. Equations for determining exposure are described in detail, with the relevant contributions due to inhalation, resuspension, and/or deposition identified in each expression.

Maximum limits for chronic exposures to depleted uranium are presented in Section III. These limits, based on health and safety standards recommended by the International Commission on Radiological Protection and the U.S. Nuclear Regulatory Commission, are discussed both for monitored personnel in restricted areas (occupational limits) and for individuals in the population (general populace limits). Estimates of exposure should be compared to these recommended maximum limits to determine compliance with prescribed standards and to identify the critical (or limiting) exposure for a given release condition.

SECTION I
MODELS FOR DETERMINING AIR AND GROUND
CONCENTRATIONS OF RELEASED DEPLETED URANIUM

This section provides a detailed description of the models used to determine concentrations of materials released to the air and ground from depleted uranium (DU) rounds used in conventional munitions. Section I,A discusses the source terms for depleted uranium used when modeling these releases. Section I,B gives an in-depth treatment of meteorological transport and deposition models. Section I,C describes the modeling of air concentrations from resuspended materials. The calculations shown here are an important adjunct to the computation of radiological and toxicological hazards resulting from the release of depleted uranium to the environment.

A. SOURCE TERMS

It is necessary to determine the number of curies for each isotope of uranium in the DU round before calculating air and ground concentrations. However the weight fractions of the uranium isotopes in DU will vary depending on the amount of ^{234}U and ^{235}U that is extracted during the enrichment process. Consequently, the specific activity of the overall DU mixture will also vary.

Differing values for the isotopic composition of DU appear in the literature, indicating different ^{235}U enrichment goals at the time of processing. Three such compositions are summarized in Table 1, Columns 1-3. The isotopic distribution

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TABLE 1
ISOTOPIC COMPOSITIONS AND SPECIFIC ACTIVITIES OF DEPLETED URANIUM

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ISOTOPE	WEIGHT FRACTION			
	BARTLETT, et al (REF. 1)	WAITE, STOETZEL, AND GILCHRIST (REF. 2)	PORTSMOUTH ENVIRONMENTAL STATEMENT (REF. 3)	LEVY (REF. 4)
^{234}U	3.4×10^{-6}	5×10^{-6}	--	8×10^{-6}
^{235}U	3×10^{-3}	2.5×10^{-3}	$2.0 \text{ to } 2.5 \times 10^{-3}$	2×10^{-3}
^{236}U	--	--	--	3.2×10^{-5}
^{238}U	9.97×10^{-1}	9.975×10^{-1}	9.98×10^{-1}	9.98×10^{-1}
Specific Activity of DU Mixture (Ci/kg)	3.6×10^{-4}	3.7×10^{-4}	3.4×10^{-4}	3.8×10^{-4}

in Column 4 is considered to be a production goal for DU in the future. This composition of DU includes the isotope ^{236}U, which is extracted during the enrichment of reprocessed fuel and not found in nature.

The specific activity of the DU mixtures in Table 1 vary from 3.4×10^{-4} Ci/kg to 3.8×10^{-4} Ci/kg. 10 CFR 20* recommends that a value of 3.6×10^{-4} Ci/kg be used for the specific activity of DU, but does not specify a corresponding isotopic composition. Using the isotopic composition in Column 1 of Table 1, an overall specific activity of 3.6×10^{-4} Ci/kg is obtained. However, this calculation employs an 0.3% weight fraction for ^{235}U, which is at the high end of the 0.2%-0.3% range observed in the literature.

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*10 CFR 20 refers to Title 10 (NRC) Code of Federal Regulations, Part 20 (Reference 5).

A weight fraction of 0.25% for ^{235}U is concluded to be a more balanced choice when defining the composition of DU since 0.25% is the midpoint in the observed range of values for this isotope. Using the weight fraction of 0.25% for ^{235}U and a specific activity of 3.6×10^{-4} Ci/kg for DU, weight fractions for ^{234}U and ^{238}U can be determined analytically by solving the following simultaneous equations:

$$x + 0.0025 + y = 1$$

$$(6.05)\ x + (2.14 \times 10^{-3})(0.0025) + (3.33 \times 10^{-4})\ y = 3.6 \times 10^{-4}$$

where

> x and y denote the weight fractions of ^{234}U and ^{238}U respectively

and

> 6.05, 2.14×10^{-3}, and 3.33×10^{-4} are the specific activities (per unit mass) of the ^{234}U, ^{235}U, and ^{238}U isotopes respectively (Ci/kg)

Thus an "average" isotopic composition of DU having a specific activity of 3.6×10^{-4} Ci/kg contains 0.00037% ^{234}U, 0.25% ^{235}U, and 99.75% ^{238}U. These weight fractions are considered representative for the varying isotopic composites of DU that may be used in the fabrication of future DU rounds and thus, in this document, are used as fixed parameter values in the equations for estimating exposures from the release of DU to the air and ground.

Table 2 contains weight fractions for the average isotopic composition of DU in the M735A1 and XM774 penetrators and the corresponding activity per penetrator for each of the three uranium isotopes in DU. Note in the column, percent of activity per penetrator, that ^{238}U is the dominant contributor to radiological dose from exposure to DU.

TABLE 2

ISOTOPIC COMPOSITION OF DEPLETED URANIUM
IN XM774 AND M735A1 PENETRATORS

T-3812a

ROUND	TOTAL MASS OF DU PER PENETRATOR (kg/round)	ISOTOPE	WEIGHT FRACTION	SPECIFIC ACTIVITY PER UNIT MASS ISOTOPE (Ci/kg)	ACTIVITY PER PENETRATOR* (Ci/round)	PERCENT ACTIVITY PER PENETRATOR
M735A1	2.18	^{234}U	3.7×10^{-6}	6.05	4.88×10^{-5}	6.2
		^{235}U	2.5×10^{-3}	2.14×10^{-3}	1.17×10^{-5}	1.5
		^{238}U	9.975×10^{-1}	3.33×10^{-4}	7.24×10^{-4}	92.3
XM774	3.40	^{234}U	3.7×10^{-6}	6.05	7.61×10^{-5}	6.2
		^{235}U	2.5×10^{-3}	2.14×10^{-3}	1.82×10^{-5}	1.5
		^{238}U	9.975×10^{-1}	3.33×10^{-4}	1.13×10^{-3}	92.3

*Activity Per $=$ Total Mass Per $\times$ Weight $\times$ Specific Activity Per
Penetrator $\quad$ Penetrator $\quad$ Fraction $\quad$ Unit Mass Isotope

B. MODELS OF METEOROLOGICAL TRANSPORT AND DEPOSITION

Models describing the transport of particles in the
air enable the following estimates to be computed:

- Instantaneous, average, or integrated
  concentration of material in the air

- Concentration of material deposited on
  the ground from the passing cloud.

Gaussian diffusion models, wherein the shape of the
cloud of released material is assumed to follow a two- or three-
dimensional Gaussian distribution, are conventionally used to
describe the transport and diffusion of materials dispersed
into the air (References 6 and 7). Such models are shown in
the literature to be fundamental solutions to Fick's equation

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for diffusion in the atmosphere (Reference 7). A basic assumption of these meteorology models is that the material released to the air is composed of gases and/or particles (less than 20 μm in diameter - Reference 8) that follow the motions of the atmosphere. This implies that the particles have negligible settling velocity and that the gas is neither positively nor negatively buoyant.

Key parameters in these Gaussian diffusion models include: effective release height of the pollutant, Pasquill atmospheric stability class, mean wind speed at the height of release, directional wind frequency (wind rose), lateral and vertical dispersion, and cloud depletion. Conservative values for these parameters should be used whenever adequate site-specific data are not available.

Different release modes (instantaneous or continuous) and durations (short-term or long-term) require different models for analysis, although all have the same Gaussian basis. For evaluating instantaneous point-source releases, puff models are employed; for analyzing continuous point-source releases, plume models are used. The following sections provide greater detail on the use of each type of model.

1. Instantaneous Releases

The Gaussian puff model simulates the diffusion and transport of instantaneous point-source releases of material to the air. A puff, once formed, dissipates with the speed and direction of the wind at the time of release. As the puff moves, it expands about its center.

Figure 1a illustrates the passage of a single puff of particles in the direction of the prevailing wind uniformly

a) PASSAGE OF A SINGLE PUFF — — SIDE VIEW

b) SAMPLE ISOPLETHS OF GROUND CONCENTRATION AFTER PASSAGE OF THE PUFF — — OVERHEAD VIEW
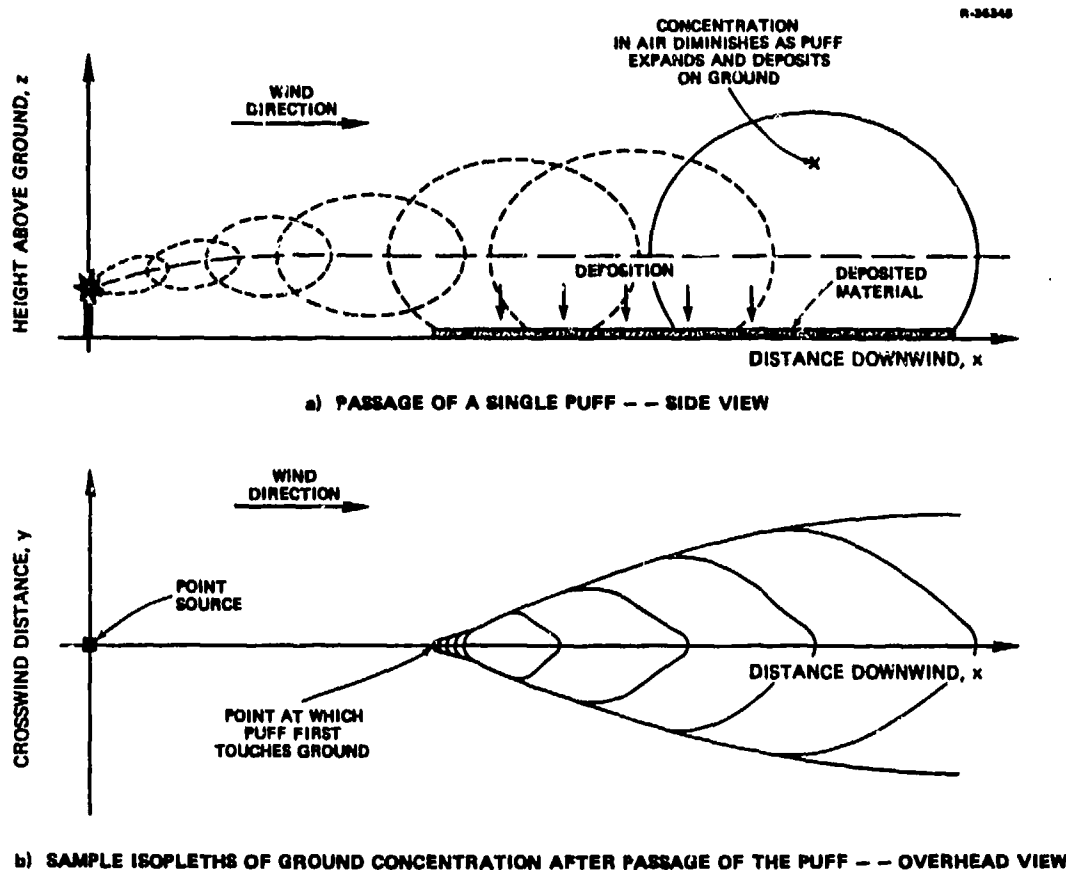
Figure 1   Passage of a Single Puff

over time. The concentrations of airborne material in the
puff diminish as distance downwind increases due to continual
expansion of the puff and deposition of material on the ground.
The concentration on the ground (Figure 1b) is seen to peak
sharply near the point at which the puff first touches the
ground and then to diminish monotonically as distance downwind
increases.

Puff Model with Constant Wind Direction - A Gaussian
puff model in which the wind direction is fixed is used for
modeling:

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- All· single, instantaneous emissions

- All multiple, instantaneous emissions
  from the same source where

  - the wind direction is known to be con-
    stant for all releases, or

  - the releases occur over a period of
    less than eight hours in duration, and
    no specific data on wind direction are
    available.

The first quantity obtained from modeling instantan-
eous releases is the instantaneous concentration, which is a
measure of the activity of radionuclides per unit volume of
air at a fixed (x,y,z) coordinate and at a fixed point in time.
It is important to note that at a fixed location instantaneous
concentration varies as the puff passes.

The instantaneous concentration of material in air at
ground level[*], χ, normalized per unit activity released, Q_0,
is calculated as follows (References 6 and 7):

$$\frac{\chi(x,y,0,t)}{Q_0} = \frac{Q_x/Q_0}{\sqrt{2}\,\pi^{3/2}\sigma_{xI}\sigma_{yI}\sigma_{zI}}\,\exp\,-\,\frac{1}{2}\left[\left(\frac{(x-\bar{u}t)^2}{\sigma_{xI}^2} + \frac{y^2}{\sigma_{yI}^2} + \frac{h^2}{\sigma_{zI}^2}\right)\right] \quad (1)$$

where

      x,y,z = positions in ⌐ Cartesian coordinate sys⸱
                    tem (Figure 1) oriented so tnat the
                    x-axis is in the direction of the hori-
                    zontal wind vecto⌐, the y-axis is cross-
                    wind, and the z-axis is vertical (m)

          t = time elapsed since emission (sec)

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*Reference 7 shows that the concentration in the air is greatest
at ground level (z=0) for all distances downwind after the puff
touches the ground. This is a conservative assumption for most
downwind distances considered in a typical analysis.

$\chi(x,y,0,t)$ = instantaneous concentration of material in a puff at time t, measured at ground level at a distance x meters downwind and y meters crosswind (Ci/m^3)

Q_0 = total activity of radionuclides released to the air in the form of airborne particles (Ci)

Q_x/Q_0 = depletion factor, or fraction of material remaining in the puff at a distance x meters downwind of the source. The remaining material is deposited on the ground by the turbulent action of the lower atmosphere. See Section I,B,3.

$\sigma_{xI}, \sigma_{yI}, \sigma_{zI}$ = standard deviation of the instantaneous distribution of material in a puff in the x, y, and z directions (m). See Table 5, Section I,B,3. In general, $\sigma_{xI} \cong \sigma_{yI}$ (Reference 8).

$\bar{u}$ = average value of wind speed in the x direction (m/sec)

h = effective height of release above ground (m). This is the height attained by the cloud after release. Since no credit is given for this rise, the effective release is set equal to the actual release height.

In order to obtain the instantaneous concentration at a fixed point, the relative (normalized) instantaneous concentration, $\chi(x,y,0,t)/Q_0$, from Equation 1 at that point is multiplied by the total activity in the puff, Q_0. Note from Equation 1 that maximum instantaneous concentration occurs along the puff centerline (i.e., y=0) at the center of the puff (i.e., $x=\bar{u}t$).

The integrated concentration represents the summation of instantaneous concentrations at a fixed (x,y,z) coordinate over the duration of the passing puff ($Ci-sec/m^3$). All radiological and toxicological measures of internal exposure from the inhalation of radionuclides use the integrated concentration

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at (x,y,z) to represent the number of curies inhaled during pas-
sage of the cloud. For this reason, <u>integrated concentration
is a more functional measure than instantaneous concentration</u>.

An analytic expression for integrated concentration,
Ψ, normalized per unit activity released is:

$$\frac{\Psi(x,y,0)}{Q_0} = \int_{t=0}^{\infty} \frac{\chi(x,y,0,t)}{Q_0} \, dt$$

$$= \frac{Q_x/Q_0}{\pi\sigma_{yI}\sigma_{zI}\bar{u}} \, \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_{yI}^2} + \frac{h^2}{\sigma_{zI}^2}\right)\right] \qquad (2)$$

where

$\Psi(x,y,0)$ = integrated concentration of material
from puff passage, measured at ground
level at a distance x meters downwind
and y meters crosswind (Ci-sec/m^3)

and $\chi(x,y,0,t)$, t, Q_0, Q_x/Q_0, σ_{yI}, σ_{zI}, $\bar{u}$, and h are as defined
in Equation 1.

To obtain the integrated concentration from the pas-
sage of one or more puffs, the relative (normalized) integrated
concentration, $\Psi(x,y,0)/Q_0$, from Equation 2 is multiplied by
the number of curies contained in all passing puffs, Q_0. Note
from Equation 2 that maximum integrated concentrations occur
along the puff centerline (i.e., y=0).

<u>Puff Model with Random Wind Direction</u> - For modeling
multiple, instantaneous emissions from the same source that

- are somewhat uniformly spaced in time, and

- occur over a period of greater than eight
  hours in duration,

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it is valid to spatially average concentrations to account for
random changes in wind direction (Reference 9). To obtain an
estimate of integrated concentration over a period which is
very long compared to that over which the mean wind speed is
computed, the technique of sector-averaging is used. This
involves (1) integrating Equation 2 with respect to y from $-\infty$
to ∞, (2) multiplying the result by the frequency with which
the wind blows toward a given 22.5 degree compass sector, and
(3) dividing by the width of that sector at the distance of
interest (Reference 7).

The sector-averaged integrated concentration, normal-
ized per unit activity released, is:

$$\frac{\Psi(r,0)}{Q_0} = \frac{f_c}{\pi r/8} \int_{y=-\infty}^{\infty} \frac{\Psi(x,y,0)}{Q_0} \, dy$$

$$= \frac{2.032 \cdot f_c \cdot (Q_x/Q_0)}{\sigma_{zI} \cdot \bar{u} \cdot r} \exp\left[-\frac{h^2}{2\sigma_{zI}^2}\right] \qquad (3)$$

where

(r,z) = positions in a cylindrical coordinate
system oriented so that r measures dis-
tance downwind within a sector and z
measures distance above the ground (m)

$\Psi(r,0)$ = sector-averaged integrated concentra-
tion of material from passing puffs,
measured at ground level at a distance
r meters downwind in a sector (Ci-sec/m^3)

f_c = fraction of time the wind blows toward
a given compass sector for a given wind
speed and atmospheric stability condition

$\pi r/8$ = arc length of a 22.5 degree sector at
downwind distance r (m)

2.032 = a constant factor from the averaging calculation, equal to $\dfrac{2}{\sqrt{2\pi}} \times \dfrac{1}{\pi/8}$

$\dfrac{\Psi(x,y,0)}{Q_0}$ = relative (normalized) integrated concentration for the puff model with constant wind direction (sec/m^3) (See Equation 2)

and Q_0, Q_x/Q_0, σ_{zI}, $\bar{u}$, and h are as defined in Equations 1 and 2.

The integrated concentration resulting from the passage of several instantaneous releases that are randomly spaced over a period of eight hours or more is obtained by multiplying the relative (normalized) integrated concentration, $\Psi(r,0)/Q_0$, from Equation 3 by the number of curies contained in all passing puffs, Q_0. Note that the concentration in the puffs are contained along the centerline (i.e., y=0) of the winds blowing into the defined sector and that $\Psi(r,0)$ is uniform across each sector at any given downwind distance r from the source.

The fraction f_c in Equation 3 generally represents a joint frequency distribution of wind direction, wind speed, and atmospheric stability class (wind rose). When wind-rose data are available, the <u>critical sector</u> -- that having the highest sector-averaged integrated concentration of any sector -- can be identified. When site-specific data are lacking, conservative values for f_c (and other model parameters) are used. Section I,B,4 treats this subject in greater detail.

<u>Deposition from Instantaneous Releases</u> - Dry deposition is defined as the removal of small particles from the passing cloud onto the ground due to nongravitational forces such as surface impact, adsorption, and electrostatic attraction. The areal density of material deposited on the ground by one or

more puffs at a given distance downwind is the product of the
ground-level integrated concentration at that distance and the
deposition velocity. The deposition velocity represents the
average downward rate of movement of the particles in a puff
due to the action of turbulent eddies near the ground (Refer-
ence 7). This can be expressed as:

$$\omega(x,y,0) = Q_0 \cdot \frac{\Psi(x,y,0)}{Q_0} \cdot v_d \tag{4}$$

for puff models with constant wind direction, or

$$\omega(r,0) = Q_0 \cdot \frac{\Psi(r,0)}{Q_0} \cdot v_d \tag{5}$$

for puff models with random wind direction, where

ω = areal density of material deposited
on the ground (Ci/m^2)

Q_0 = total activity emitted in single or
multiple instantaneous releases from
the same source (Ci)

v_d = deposition velocity[*] (m/sec)

and $\Psi(x,y,0)/Q_0$ and $\Psi(r,0)/Q_0$ are determined from Equations 2
and 3, respectively.

The entire cloud is eventually depleted onto the ground
at an infinitely large downwind distance. Note that the spatial
profile of the ground concentration ω follows the Gaussian
pattern of the integrated air concentration Ψ at ground level

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[*]Based on the assumptions of neutral buoyancy and negligible
settling of particles for the Gaussian diffusion model, the
value of 0.01 m/sec (Reference 10 and Section 5.3, Reference
7) is an acceptable estimate of deposition velocity.

(see Figure 1). The areal density of deposited radionuclides
is of primary importance in computing external radiological
dose and in computing concentrations of resuspended material
in air (Section I,B).

2. Continuous Releases

A continuous Gaussian plume results from the addition
of an infinite number of overlapping puffs carried in the direc-
tion of the wind (Reference 7). The advective transport of
these puff elements and the diffusion of the elements about
their individual centers cause dispersion of the plume (Refer-
ence 6). The activity of material released is expressed in
terms of a release rate (Ci/sec) and the downwind material
distribution is measured in terms of the average concentration
(Ci/m^3) over the period of release.

Figure 2 illustrates the Gaussian distribution of a
plume in the horizontal and vertical directions. The plume
width is seen to expand as distance downwind increases. Ground
concentration under the plume (not shown) peaks near the point
at which the plume first touches the ground and then diminishes
monotonically as distance downwind increases.

Plume Model with Constant Wind Direction - A plume
model having a fixed wind direction is used to compute concen-
trations from continuous releases of less than eight hours in
duration and when no specific data on wind direction are avail-
able. The short-term average concentration, the most important
measure associated with the constant-wind plume model, is de-
fined as the average concentration of the diffusing puff ele-
ments at each downwind location.

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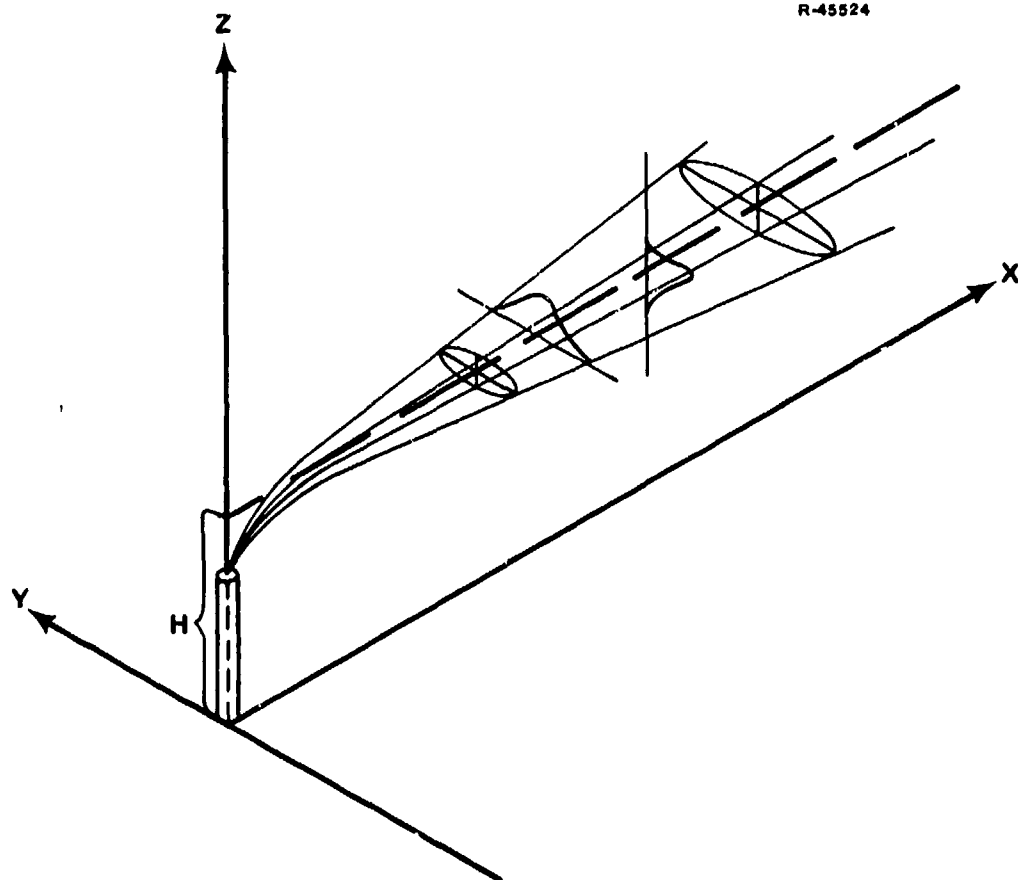
Figure 2   Gaussian Plume Distribution
(Adapted from Reference 8)

An analytic representation for the short-term average concentration of material in air at ground level[*] normalized per unit rate of activity released is:

$$\frac{\bar{\chi}(x,y,0)}{Q_0^{'}} = \frac{Q_x^{'}/Q_0^{'}}{\pi \sigma_y \sigma_z \bar{u}} \ \exp\left[-\ \frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2}\right)\right] \qquad (6)$$

where

$\bar{\chi}(x,y,0)$ = short-term average concentration of material in a plume, measured at ground level at a distance x meters downwind and y meters crosswind (Ci/m^3)

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*See footnote on p. 7.

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$Q_0' = $ release rate of material to the air (Ci/sec)

. $Q_x'/Q_0' = $ depletion factor, or fraction of material remaining in the plume at a distance x meters downwind from the source. The remainder is deposited on the ground by the turbulent action of the lower atmosphere. See Section I,B,3.

$\sigma_y, \sigma_z = $ steady-state standard deviations of the plume in the y and z directions (m). See Table 6, Section I,B,3

$\bar{u} = $ average value of wind speed in the x direction (m/sec)

$h = $ effective height of release above the ground (m). Since no credit is given for plume rise, the effective release is set equal to the actual release height

The short-term average concentration resulting from a continuous release of eight hours or less in duration is determined by multiplying the relative (normalized) average concentration, $\bar{\chi}(x,y,0)/Q_0'$, from Equation 6 by the constant release rate, Q_0'. Note from Equation 6 that short-term average concentrations are highest along the plume centerline (i.e., y=0).

Plume Model with Random Wind Direction - For continuous releases of greater than eight hours in duration, it is valid to spatially average the short-term plume concentration (Equation 6) to account for random changes in wind direction (Reference 9). To obtain an estimate of long-term average concentration over a period of release greater than eight hours in duration, a sector-averaging procedure, analogous to that presented in Section I,B,1 for the puff model, is used.

The long-term average concentration normalized per unit rate of activity released is:

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$$\frac{\bar{\chi}(r,0)}{Q_0'} = \frac{f_c}{\pi r/8} \int_{y=-\infty}^{\infty} \frac{\bar{\chi}(x,y,0)}{Q_0'} \, dy$$

$$= \frac{2.032 \cdot f_c (Q_x'/Q_0')}{\sigma_z \cdot \bar{u} \cdot r} \exp\left[-\frac{h^2}{2\sigma_z^2}\right] \tag{7}$$

where

$\bar{\chi}(r,0)$ = long-term average concentration of material in a plume, measured at ground level at a distance r meters downwind in a sector (Ci/m^3)

f_c = fraction of time the wind blows toward a given 22.5-degree compass sector for a given wind speed and atmospheric stability condition

$\pi r/8$ = arc length of a 22.5-degree sector at downwind distance r (m)

2.032 = a constant factor from the averaging calculation, equal to $\dfrac{2}{\sqrt{2\pi}} \times \dfrac{1}{\pi/8}$

$\dfrac{\bar{\chi}(x,y,0)}{Q_0'}$ = relative (normalized) short-term average concentration for the plume model with constant wind direction (see Equation 6)

and Q_0', Q_x'/Q_0', σ_z, $\bar{u}$, and h are as defined in Equation 6.

The long-term average concentration resulting from a continuous release of greater than eight hours in duration is determined by multiplying the relative (normalized) average concentration, $\bar{\chi}(r,0)/Q_0'$, from Equation 7 by the constant release rate, Q_0'. Average concentrations from long-term continuous releases are uniform across each compass sector at any given downwind distance r from the source.

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A site-specific wind rose may be used to represent the long-term joint frequency distribution of wind direction, wind speed, and atmospheric stability class (i.e., f_c in Equation 7). When wind rose data are available, the critical sector (that having the highest long-term average concentration of any sector) can be identified. When site-specific data are lacking, conservative values for f_c (and other model parameters) are used. Section I,B,4 treats this subject in greater detail.

Deposition from Continuous Releases - Dry deposition depletes material from the plume in a manner analogous to that presented for the puff (Section I,B,1). The areal density of material deposited on the ground at a given point (receptor) is a function of the integrated concentration, duration of exposure to the passing plume, and deposition velocity. Integrated concentration from a continuous release is obtained by multiplying the average concentration, $\bar{\chi}(x,y,0)$ or $\bar{\chi}(r,0)$, by the duration of exposure to the plume, T. If the receptor is present during the entire passage of the plume, then $T = Q_0/Q_0'$ and the integrated concentration becomes simply the product of relative average concentration times total activity released (i.e., $\bar{\chi}/Q_0'$ times Q_0). More generally, deposition from continuous releases can be expressed as:

$$\omega(x,y,0) = Q_0' \cdot \frac{\bar{\chi}(x,y,0)}{Q_0'} \cdot T \cdot v_d \qquad (8)$$

for the plume model with constant wind direction, or

$$\omega(r,0) = Q_0' \cdot \frac{\bar{\chi}(r,0)}{Q_0'} \cdot T \cdot v_d \qquad (9)$$

for the plume model with random wind direction, where

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ω = areal density of material deposited on the ground (Ci/m^2)

Q_0' = release rate of material to the air (Ci/sec)

T = duration of exposure of the ground to the passing plume (sec). Note that for computing deposition from passage of the <u>entire</u> plume, $T=Q_0/Q_0'$, where Q_0 is the total number of curies released

v_d = deposition velocity[*] (m/sec)

and $\bar{\chi}(x,y,0)/Q_0'$ and $\bar{\chi}(r,0)/Q_0'$ are determined from Equations 6 and 7, respectively.

Note that the spatial profile of the ground concentration ω follows the distribution of the average air concentration $\bar{\chi}$ at ground level. The areal density of deposited radionuclides is of primary importance in computing external radiological dose and in computing concentrations of resuspended material in air (see Section I,C).

3. Atmospheric Stability, Standard Deviations, and Depletion Factor

Stability conditions in the lower atmosphere effect the expansion of the cloud as it moves downwind from the point of release and the amount of material remaining in the cloud (or conversely, depositing on the ground) at downwind distances. A number of factors influence stability including wind speed, time of day, incoming solar radiation, and cloud cover. A common method for determining atmospheric stability is to measure the vertical temperature difference between the release height

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[*]See footnote on p. 12.

and the 10-meter level above ground (Reference 11). Stability
classes using the temperature difference method are given in
Table 3. When temperature decreases with height at a fast rate,
the atmosphere is in <u>unstable</u> equilibrium and vertical motions
are enhanced. When temperature increases rapidly with height
(inversion), vertical motions are damped or reduced (stable
equilibrium).

TABLE 3

CLASSIFICATION OF ATMOSPHERIC STABILITY
(Temperature Difference Method)

STABILITY CLASSIFICATION		TEMPERATURE CHANGE WITH HEIGHT (°C/100m)
Extremely unstable	A	<-1.9
Moderately unstable	B	-1.9 to -1.7
Slightly unstable	C	-1.7 to -1.5
Neutral	D	-1.5 to -0.5
Slightly stable	E	-0.5 to 1.5
Moderately stable	F	1.5 to 4.0
Extremely stable	G	>4.0

Source: Reference 11.

Another method which has wide application for deter-
mining the degree of turbulence in the lower atmosphere was
introduced by Pasquill (Reference 12). The stability of the
atmosphere is estimated from the wind speed at a height of
about 10 meters and from the incoming solar radiation during
the day or the cloud cover during the night (Reference 8).
Stability categories using Pasquill's method are given in
Table 4. This stability classification is representative of

TABLE 4

KEY TO STABILITY CATEGORIES
(Pasquill Method)

A - Extremely unstable conditions   D - Neutral conditions[†]

B - Moderately unstable conditions   E - Slightly stable conditions

C - Slightly unstable conditions   F - Moderately stable conditions

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SURFACE WIND SPEED (at 10m), m/sec	DAYTIME ISOLATION			NIGHTTIME CONDITIONS	
	STRONG	MODERATE	SLIGHT	THIN OVERCAST OR $\geq$ 4/8 CLOUDINESS[††]	$\leq$ 3/8 CLOUDINESS
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

†Applicable to heavy overcast, day or night.

††The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

Source: Reference 12.

atmospheric conditions in open country or rural areas, but is less reliable for urban areas. Differences are due primarily to the influence of the city's larger surface roughness and heat island effects upon the stability regime. The greatest difference in atmospheric stability between rural and urban areas occurs on calm clear nights. On such nights conditions over rural areas are very stable; but over urban areas, conditions are slightly unstable or neutral to a height several times the average building height, with a stable layer above (Reference 12).

The <u>standard deviations</u> (σ_{yI}, σ_{zI}, σ_y, and σ_z) for puff and plume expansion increase with increasing distance downwind from the source. The rate at which these dispersion

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coefficients increase with downwind distance is a function of the turbulent nature of the atmosphere. This relationship is commonly modeled using a power-law function (e.g., $\sigma = ax^b$), where the coefficients a and b vary with atmospheric stability. Power function coefficients for determining puff and plume dispersion are given in Tables 5 and 6 respectively. (Typical analytic and graphic relationships for puff and plume standard deviations can be found in References 7, 8, 13, and 14). For stable (E, F, or G) atmospheric conditions, the σ's increase at a relatively slow rate; for neutral (D) and unstable (A, B, or C) conditions, the σ's increase at a moderate and fast rate, respectively.

TABLE 5

STANDARD DEVIATIONS FOR PUFF RELEASES

STABILITY CLASS	$\sigma_{zI} = ex^f$		$\sigma_{yI} = gx^h$	
	e	f	g	h
	$100 \leq x \leq 4000$	$100 \leq x \leq 4000$	$100 \leq x \leq 4000$	$100 \leq x \leq 4000$
A B	0.53	0.73	0.14	0.92
C D	C.15	0.70	0.06	0.92
E F	0.05	0.61	0.02	0.89
G	0.03	0.61	0.013	0.89

Source: Reference 7 - Stability Classes A-F
Reference 14 - Stability Class G

Note: Variable x represents downwind distance (m) from source.

The depletion factors for puff and plume releases $(Q_x/Q_0$ and $Q_x'/Q_0')$ at a given downwind distance depend on the standard deviations, effective release height, wind speed, and

TABLE 6

STANDARD DEVIATIONS FOR PLUME RELEASES

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STABILITY CLASS	$\sigma_z = ax^b$						$\sigma_y = cx^d$			
	a			b			c		d	
	x<500	500≤x<5000	x≥5000	x<500	500<x<5000	x≥5000	x<10000	x≥10000	x<10000	x≥10000
A	0.0383	0.000254	0.000254	1.281	2.089	2.089	0.495	0.606	0.873	0.851
B	0.1393	0.0494	0.0494	0.9467	1.114	1.114	0.310	0.523	0.897	0.840
C	0.112	0.101	0.115	0.910	0.926	0.911	0.197	0.285	0.908	0.867
DD Day	0.0856	0.259	0.737	0.865	0.687	0.564	0.122	0.193	0.916	0.865
DN Night	0.0818	0.253	1.297	0.8155	0.634	0.442	0.122	0.193	0.916	0.865
E	0.1094	0.2452	0.9204	0.7657	0.6358	0.4805	0.093	0.141	0.912	0.868
F	0.05645	0.1930	1.505	0.805	0.6072	0.3662	0.0625	0.0800	0.911	0.864
G	0.03387	0.1158	0.903	0.805	0.6072	0.3662	0.0417	0.0533	0.911	0.864

Source: Reference 13 - Stability Classes A-F
Reference 14 - Stability Class G

Note: Coefficients are based on a 10-minute averaging time. Variable x represents downwind distance (m) from source.

deposition velocity. For stable conditions, the fraction of material in the cloud deposited on the ground increases rapidly as distance downwind increases; neutral and unstable conditions are characterized by moderate and slow rates of deposition, respectively, as distance downwind increases.

Depletion factors can be evaluated using the analyses of Van der Hoven (Reference 7, Section 5.3-2)

$$Q_x/Q_0 = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2} \left(\frac{v_d}{\bar{u}}\right) \int_0^{x'} \frac{1}{\sigma_{zI}} \exp\left(-\frac{h^2}{2\sigma_{zI}^2}\right) dx \right] \quad (10)$$

for puff releases, or

$$Q_x'/Q_0' = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2} \left(\frac{v_d}{\bar{u}}\right) \int_0^{x'} \frac{1}{\sigma_z} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) dx \right] \quad (11)$$

for plume releases, where x' is downwind distance and v_d, $\bar{u}$, σ_{zI}, h, and σ_z are defined in Equations 1 and 6. When Q'_x/Q'_0 is set equal to 1, all the material released is assumed to remain in the cloud at each downwind distance, yielding conservatively high estimates of the air concentration.

4. Guidelines for Model Use

In a specific application, when sufficient meteorological data are gathered, these values may be used to calibrate the released puff or plume (Sections I,B,1 and I,B,2). However appropriate data may not be available cr may exist only in the form of long-term averages. As a result, guidelines have been established (References 6 and 9) to introduce an appropriate degree of conservatism into the calculations whenever there are uncertainties in the data, or whenever there is not sufficient information available to fully characterize site conditions.

NRC Regulatory Guide 1.3 (Reference 9) provides a framework for selecting a conservative model type and parameter values whenever sufficient site-specific data is not available. The nature of a release, instantaneous or continuous, dictates whether the puff or plume model is used; the duration of the release determines whether the constant or random wind approach is used and the nature of the data, site-specific or NRC-recommended, that may be employed. These guidelines are summarized in Table 7 by release duration.

For releases of up to eight hours in duration, a constant wind model must be used. When releases are eight hours or more in duration, a random wind model employing sector-averaging may be used. NRC-recommended parameter values should be used with either a constant wind or random wind model for releases of up to 30 days. These parameter values will provide a conservative bound on the estimates of air concentration. (The use

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TABLE 7
GUIDELINES FOR SELECTING GAUSSIAN DIFFUSION
MODELS AND PARAMETER VALUES

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RELEASE DURATION	TYPE OF MODEL AND DATA TO USE	RELEASE HEIGHT, h	DEFAULT PARAMETER VALUES		
			PASQUILL STABILITY CLASS(ES)	WIND SPEED BY STABILITY CLASS, $\bar{u}$	WIND ROSE FACTOR, f_c
0-8 hours	• Constant wind	Ground-level	100% F-stability	1 m/sec	–
	• Recommended data	Elevated	Envelope of Pasquill categories (Figure A7, Reference 6)	1 m/sec	–
8-24 hours	• Random wind	Ground-level	100% F-stability	1 m/sec	1.0
	• Recommended data	Elevated	Envelope of Pasquill categories	1 m/sec	1.0
1-4 days	• Random wind • Recommended data	Ground-level	40% D-stability 60% F-stability	3 m/sec (D-stability) 2 m/sec (F-stability)	1.0
		Elevated	Maximum[†] of: 1) 40% A-stability 60% C-stability 2) 50% C-stability 50% D-stability 3) 33.3% C-stability 33.3% D-stability 33.3% E-stability 4) 33.3% D-stability 33.3% E-stability 33.3% F-stability 5) 50% D-stability 50% F-stability	2 m/sec (A-, B-, E-, and F-stability) 3 m/sec	1.0
> 4 days	Releases of 4-30 days: • Random wind • Recommended data Releases of 30 days: • Random wind • Recommended or average long-term, site-specific data	Ground-level	33.3% C-stability 33.3% D-stability 33.3% F-stability	3 m/sec (C- and D-stability) 2 m/sec (F-stability)	0.33
		Elevated	Maximum[†] of: 1) 40% A-stability 60% C-stability 2) 50% C-stability 50% D-stability 3) 33.3% C-stability 33.3% D-stability 33.3% E-stability 4) 33.3% D-stability 33.3% E-stability 33.3% F-stability 5) 50% D-stability 50% F-stability	2 m/sec (A-, B-, E-, and F-stability) 3 m/sec (C- and D-stability)	0.33

†Choose the combination that yields the highest concentration at a given downwind distance.

Source: Reference 9.

of average long-term, site-specific data cannot be employed effectively for short-term releases with any degree of certainty.)

When releases of 30 days or more are evaluated, either average long-term, site-specific data or the more conservative, NRC-recommended values may be used. Note from Table 7 that the use of recommended data sometimes involves fractional occurrences of two or more stability classes. This is done to more realistically simulate the day-to-day variation in stability class that occurs at any location.

In summary, Table 7 provides a framework for selecting the appropriate diffusion model and parameter values to insure that a conservative estimate of air concentration will be obtained when sufficient meteorological data are not available. However, when site-specific, meteorological data are measured in conjunction with a puff or plume release, these data may be used in the model regardless of the duration of release.

C. RESUSPENSION OF SURFACE PARTICLES

Material from the passing cloud which is displaced by wind or by human activity forms a secondary source of material which contributes to the air concentration downwind both during and after passage of the cloud. Evaluation of airborne concentration of dispersed material should include concentrations due to both primary and resuspended sources. This section outlines a general analytic treatment of resuspension.

1. Resuspension Factor

The simplest model of air concentration due to resuspension of deposited material is one in which the resuspended

air concentration is expressed as the product of ground concentration and a _resuspension factor_ (References 10 and 15). The resuspension factor (ratio of local air concentration to local ground concentration) is used to convert the ground concentration into an estimate of average air concentration due to all potential resuspensions of the deposited material. The resuspended air concentration can be expressed in terms of Gaussian puff or plume model variables as:

$$\bar{\chi}_r(x,y,0) = K_r \cdot \omega(x,y,0) \qquad (12)$$

for constant wind-direction models, or

$$\bar{\chi}_r(r,0) = K_r \cdot \omega(r,0) \qquad (13)$$

for random wind-direction models, where

$\bar{\chi}_r$ = average concentration of resuspended particles in air at ground level (Ci/m^3)

K_r = resuspension factor $(1/m)$

ω = areal density of material deposited during initial cloud passage (Ci/m^2)

Resuspension factors are determined largely by empirical measurements of average ground and air concentrations and are dependent on many site-specific factors such as:

- Surface conditions (degree of moisture, roughness, agriculture)

- Nature of particulates deposited (particle size, compound, isotope)

- Local meteorology (humidity, wind speed)

- Degree of agitation by motor or pedestrian traffic.

Most resuspension factors are based on measurements made in semi-desert regions, and their direct applicability to soils having other characteristics is questionable. For example, resuspension factors applicable to dry surfaces would most likely tend to overestimate the extent of resuspension in more humid environments. One reason for this is that material deposited on soil tends to mix with the surface layer and is transported below the surface by precipitation. However, the decrease in surface activity via leaching can be estimated in more humid environments using a nuclide-specific environmental loss factor. Such an approach has been taken in modeling efforts for the Liquid Metal Fast Breeder Reactor (Reference 15) and the WASH-1400 Reactor Safety Study (Reference 10). According to Reference 10, initial resuspension factors can range from 10^{-2}/m to 10^{-10}/m depending on the nature of the deposition surface, the degree to which the deposited material is agitated, and the degree to which upwind concentration distributions contribute to resuspended concentrations. Therefore, obtaining site-specific data is very important when using resuspension factors.

2. Bounding the Overall Concentration in Air

Another perspective on resuspension is gained through a mathematical analysis of the processes of deposition and resuspension. Horst's study (Reference 16) concluded that under very general conditions the air concentration due to both the depleted initial cloud and the resuspended cloud is less than or equal to that due to the initial cloud without allowing for depletion by deposition. In other words, a very conservative estimate of the air concentration or exposure from both initial cloud passage and resuspension may be made by simply computing the concentration due to the undepleted cloud. The only qualification to this conservatism is the

neglect of redeposition. However, it is likely that the impact of redeposition is small, since its net effect is to reduce the resuspended air concentration. Additionally, several model conservatisms would tend to more than offset the neglect of redeposition. For instance, losses due to leaching of weathered material, which can be substantial, are not considered. In addition, Horst calculates exposure to the resuspended air concentration over the entire period required to resuspend all of the deposited material. Since a single receptor may not be exposed for this extended period, this assumption is also conservative.

3. Methodology for Analysis of Resuspension

To summarize, two approaches are suggested in the literature for modeling resuspension. In the "constant factor" approach, the ground concentration at a given point is multiplied by a constant factor to obtain a resuspended air concentration. In the "bounding approach", the undepleted concentration of the original cloud is considered an upper bound for the concentration due to both the initial cloud corrected for depletion and resuspension of the deposited material. Based on these approaches, the following general methodologies may be used to account for resuspension:

- Whenever enough site-specific data can be collected for the areas adjacent to a release point, the "constant factor" approach is used. A value for the resuspension factor (K_r) is selected based on the best match of site parameters with empirical data, and Equations 12 or 13 is used to compute the average concentration due to resuspended particles. A corresponding duration of exposure is assumed for the particular measure being computed. Air concentrations from the initial cloud and areal densities of deposited materials are computed using the procedures described in Section I,B.

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- If site-specific data are lacking, the "bounding approach" is used to provide an upper limit on exposure due to inhalation of both the initial cloud and the resuspended cloud. The required computations for the integrated or average concentration due to primary inhalation and resuspension involve the use of Equations 2 or 3 (for puff models) or Equations 6 or 7 (for plume models) without the Q_x/Q_0 or Q_x'/Q_0' depletion factors.

Whenever the impact of resuspension is to be evaluated, the first technique is preferred because it does not produce overly conservative results. However, this procedure can only be applied effectively when site-specific data are available.

SECTION II.
METHODS FOR CALCULATING RADIOLOGICAL AND
TOXICOLOGICAL EXPOSURE MEASURES

In this section the equations used to calculate exposure measures from releases of DU to the air and ground are presented, along with general criteria for their use. The calculations are based primarily on procedures outlined in References 5, 7, 9, and 17. Although the discussion in this section focuses on chronic exposures, the following equations may also be used to evaluate acute exposures.

Throughout this section, two classes of exposure are considered: occupational exposure and exposure to the general populace. Occupationally exposed persons must be 18 years of age or older and must submit to frequent monitoring for radiological or toxicological insult. Members of the general populace, on the other hand, are not monitored and include children, for whom lower dose limits are prescribed. Additional differences between these two groups include different rates of respiration, different potential exposure times to harmful substances (i.e., 40 hours per week for occupational exposures versus 168 hours per week for general populace exposures), and different periods of time over which the exposure measures are to be computed.

All exposure measures described in the following sections consider the effects of internal buildup of inhaled uranium within the body or its organs. Additionally, dose calculations for the whole body and critical organs incorporate irradiation from external sources. The effect of radioactive decay on

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concentration is negligible due to the long half-lives of the
uranium isotopes, and thus is not included explicitly in the
equations.

A.   CRITERIA FOR DETERMINING THE LIMITING EXPOSURE MEASURE

Radiation dose and chemical toxicity are important
measures of human exposure to depleted uranium. A radiation
dose can occur from either internal or external exposures,
while toxicological effects are produced solely by concentra-
tions of DU within the body. In any situation, it is neces-
sary to consider such factors as the isotopic composition and
solubility of the DU compounds as well as the potential path-
ways of exposure (internal and/or external) before deciding
whether radiation or toxicity is the more critical concern.

Depleted uranium may be released to the air and ground
in the form of either soluble or insoluble compounds. The most
important aspect of solubility is its potential for translocat-
ing and concentrating inhaled uranium compounds within the
various body organs. The maximum amount of insoluble DU that
may be inhaled is governed by the dose of radiation received
by the lungs, which is the point of entry into the body. When
compounds of DU are soluble, chemical damage to the kidney is
of greater concern than radiological damage to the lungs.
(Radiation effects from inhaled soluble compounds of uranium
dominate only when the mixture is highly enriched in ^{235}U
(Reference 18).)

Thus, initial assessments of DU contamination should
include an evolution of all possible exposures. For assessing
potential hazards from insoluble DU, radiation dose from both

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internal and external sources and average radiological concentration in air are determined; for assessing risks from soluble DU, an estimate of chemical toxicity is computed. From these determinations, the limiting exposure(s) will become evident; all future evaluations for the same operating conditions need focus only on the critical measures(s).

B. RADIATION DOSE

1. Whole-Body and Critical-Organ Dose

The organs and tissues of the body respond to radiation in varying degree. The effect of radiation on body organs depends on both the magnitude of the dose delivered and the essential function performed by the organ. Thus, some organs and tissues are more susceptible to the circumstances under which they are irradiated and are said to be critical.

In the case of whole-body irradiation, the critical organs and tissues are taken to be the blood-forming organs, the gonads, and the lenses of the eyes. Any dose to the whole body from internal or external sources is assumed to uniformly affect these organs. When irradiation is more or less limited to portions of the body, the critical organ is that organ most likely to be permanently damaged either because of its inherent radiosensitivity, or because of a combination of radiosensitivity and localized high dose. The critical body organ is generally one of the following: lung, gastro-intestinal (GI) system (lower large intestine), bone, or kidney. Other portions of the body may receive radiation (primarily from external sources), but are not usually considered to be critical. These include the skin, forearms and hands, and ankles and feet (Reference 19).

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Whole-body dose is computed as the sum of (1) internal dose to the whole body from inhalation of radionuclides, (2) external gamma dose from deposited radionuclides, and (3) internal whole-body dose from the inhalation of resuspended radionuclides. Critical-organ dose is computed as the sum of (1) internal dose to the critical organ from inhalation of radionuclides, (2) external gamma dose from deposited radionuclides, and (3) internal critical-organ dose from the inhalation of resuspended radionuclides. The calculations shown here are for dose from insoluble compounds of uranium only, for which the lung is the critical organ. The effect of solubility on whole-body and critical-organ dose is discussed in Section II,B,2.

Whole-body and critical organ doses, averaged annually for both workers and members of the general populace, are calculated using the following expression:

$$D_{jk\ell} = \left[f_a \cdot f_b \cdot N_\ell \cdot B_k \cdot \sum_i (A_i \cdot DFI_{ij}) \right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[f_a \cdot M_\ell \cdot v_d \cdot T_{k\ell} \cdot \sum_i (A_i \cdot DFD_{ij}) \right] \cdot F \qquad \text{(deposition)}$$

$$+ \left[f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot T_{k\ell} \cdot B_k \cdot \sum_i (A_i \cdot DFI_{ij}) \right] \cdot F \quad \text{(resuspension)}$$

$$(14)$$

where

$D_{jk\ell}$ = total radiological dose to organ j of a person in population class k during period ℓ (rem)

i = radionuclide index (1=^{234}U, 2=^{235}U, 3=^{238}U)

j = body organ index (1=whole body, 2=critical organ)

k = population class index (1=occupational, 2=general populace)

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ℓ = index of the averaging period used (1=annual, 2=quarterly, 3=weekly, 4=user specified)

f_a = fraction of available DU that is dispersed to the air as aerosols (particles <20 µm AED)

f_b = fraction of aerosolized DU that is respirable (particles $\leq$ 3 µm AED)

N_ℓ = amount of DU available for release to the air during averaging period ℓ (kg)

B_k = breathing rate for a person in population class k (m^3/sec)

A_i = number of curies of radionuclide i per unit mass of DU (Ci/kg)

DFI_{ij} = fifty-year dose commitment factor for organ j from inhalation (chronic or acute) of radionuclide i in insoluble form (rem/Ci)

F = normalized concentration of material in the passing cloud at a ground-level receptor (Ψ/Q_0 for puffs or $\bar{\chi}/Q_0'$ for plumes -- see Section I) (sec/m^3)

$$M_\ell = \frac{\left[\begin{array}{l} \text{Amount of DU} \\ \text{accumulated} \\ \text{through beginning} \\ \text{of final averaging} \\ \text{period } \ell \end{array} \; + \; \begin{array}{l} \text{Amount of DU} \\ \text{accumulated} \\ \text{through end} \\ \text{of final averaging} \\ \text{period } \ell \end{array}\right]}{2} \quad (kg)$$

When the actual duration of release $\leq$ the averaging period, $M_\ell = N_\ell$.

v_d = deposition velocity (m/sec)

$T_{k\ell}$ = duration of exposure of persons in population class k to air or ground concentrations in averaging period ℓ (sec)

DFD_{ij} = dose factor for external exposure (chronic) of organ j one meter above a uniformly distributed areal density of radionuclide i $\left(\dfrac{\text{rem/sec}}{\text{Ci}/m^2}\right)$

$$K_r = \text{resuspension factor} = \frac{\text{concentration of respirable DU in the air}}{\text{concentration of aerosolized DU on the ground}} \quad (1/m)$$

(See Section I,C)

Values for several of the above parameters are given in Table 8, p. 41.

2. Impact of Solubility on Radiation Doses

The radiation dose calculations presented in Section II,B,1 are based on the Reference Man model and parameters for insoluble uranium described by the International Commission on Radiological Protection (ICRP) (Reference 19). A recent study (Reference 20) revealed that approximately 40% of the airborne respirable DU particles were observed to dissolve in simulated lung fluid within seven days. Therefore it is necessary to consider the possible effects of solubility on the radiation dose calculations in Section II,B,1.

It is possible to bound the range of radiation doses by examining two extreme cases: complete solubility and complete insolubility. Figure 3 is a block diagram of the ICRP Reference Man model for internal radiation dosimetry. It can be seen that the major difference between pathways for soluble and insoluble compounds that have been inhaled is the rapid entry of soluble compounds into the bloodstream. For soluble compounds, essentially all material (25% of the total amount inhaled) reaching the lungs quickly enters the bloodstream. For insoluble compounds, about half of the insoluble material (12.5% of the total amount inhaled) remains in the lungs for a time period (characteristic time, T_B, of 120 days) before entering the bloodstream. The other half is expelled from the
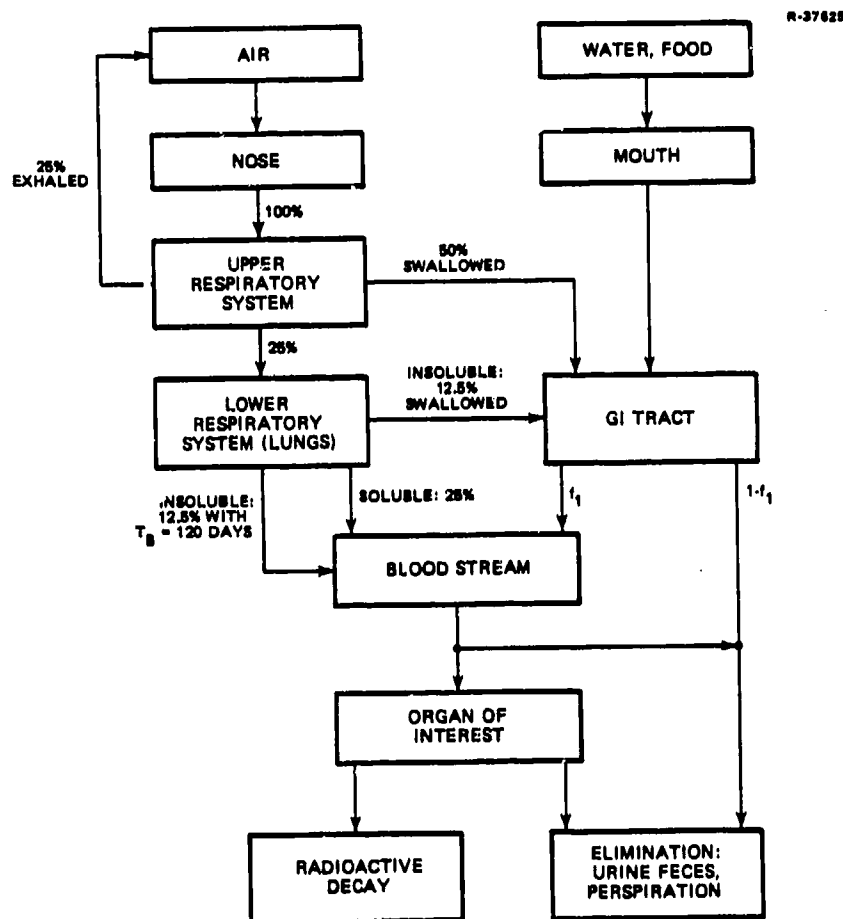
Figure 3   ICRP Reference Man Model for Internal
            Radiation Dosimetry

lungs and enters the GI tract through swallowing. None of the
swallowed insoluble material and only a small portion of the
soluble material reaching the GI tract enters the bloodstream.
ICRP (Reference 19) gives a value of 0.01 for f_1 in Figure 3,
i.e., the transfer coefficient from the GI tract to the blood
for soluble compounds. Thus for insoluble compounds, 12.5% of
the total matter inhaled eventually enters the bloodstream --
compared to [25% + (50%)(0.01)] $\cong$ 25.5% when the material is
soluble.

Radiation doses to all organs other than the lungs and lower large intestine result from the transport of radionuclides through the blood. Since about twice the amount of uranium enters the bloodstream when the inhaled material is soluble rather than insoluble, doses to organs other than the lungs and lower large intestine will be about twice as large for soluble uranium compounds as for insoluble compounds. The dose to the lungs and lower large intestine, on the other hand, will decrease. Consequently, the whole-body dose, which is a weighted sum of the radiation doses to all the organs, can be no more than twice as large when soluble compounds are inhaled instead of insoluble compounds*.

When the inhaled compounds are insoluble, the lung is the critical organ. It can be shown from the ICRP model and the dose commitment factors in Reference 21 that the radiological dose (amount × dose commitment) to any organ from inhaled soluble compounds of uranium is always less than the dose to the lungs from insoluble compounds. Therefore, the critical-organ dose will not be larger for soluble compounds than for insoluble compounds. Since radiological dose to the lung from soluble compounds of uranium is small, another organ will become the critical organ.

C.   EXPOSURE TO CONCENTRATIONS OF DEPLETED URANIUM IN AIR

The average concentration of DU in air to which a person is exposed for a period of time is a general measure used to estimate exposure to depleted uranium. This measure

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*Note that the whole-body dose due to inhalation of airborne and resuspended insoluble uranium compounds is only a portion of the total whole-body dose for occupational and general populace exposures. The remainder dose is supplied by gamma radiation from radionuclides deposited on the ground. Therefore this factor-of-two bound on whole-body dose is conservatively high.

is determined separately for occupational and general populace exposures. Various forms of this measure have been established to consider both (1) the radiological properties of soluble and insoluble uranium and (2) the toxicological properties of soluble uranium. Average concentrations are based on both material in the passing cloud and material that is deposited by the cloud and subsequently resuspended.

1. Radiological Concentrations

The average radiological concentration of DU in air to which an individual is exposed over a period of time (μCi/ mℓ) determines the inhalation dose commitment for the critical organ. An equivalent measure is the total intake of radioactive material (μCi) during the period, which is obtained by multiplying the average concentration by the amount (mℓ) of air inhaled in the period. Separate maximum permissible concentration (MPC_a) limits are specified for radiological concentrations of soluble and insoluble compounds of uranium in air for both occupational and general populace exposures (Section III,B,1). It should be noted that the use of MPC_a standards alone is only valid if there are no significant contributions from external sources of radiation (Reference 19). This topic is discussed in greater detail in Section III,B,1.

The average radiological concentration in air is computed quarterly for occupational exposures and annually for general populace exposures using the following equation:

$$C_{k\ell}^R = \left[\frac{f_a \cdot f_b \cdot N_\ell \cdot 1 \cdot \sum_i A_i}{T_{k\ell}} \right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot 1 \cdot \sum_i A_i \right] \cdot F \qquad \text{(resuspension)} \qquad (15)$$

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where

$$C_{k\ell}^R = \text{average radiological concentration of DU in air to which a person in population class k is exposed during averaging period } \ell \; (\mu Ci/m\ell)$$

$$1 = \text{conversion factor } \left(\frac{\mu Ci/m\ell}{Ci/m^3}\right)$$

and all other variables are as defined in Equation 14.

2. Toxicological Concentrations

Average Toxicological Concentration - When water-soluble compounds of uranium are airborne, chemical toxicity may be a more limiting factor than radiological activity (Section II,A). Accordingly, an additional measure for estimating exposure to airborne concentrations of uranium is the average concentration of soluble uranium in air (mg/m^3) to which a person is exposed in a work week (occupational exposure) or in a year (general populace exposure). Maximum permissible limits for toxic concentrations of soluble uranium in air are given in Section III,B,2 for both occupational and general populace exposures.

The average toxicological concentration in air is expressed as:

$$C_{k\ell}^T = \left[\frac{f_a \cdot f_b \cdot N_\ell \cdot 10^6}{T_{k\ell}}\right] \cdot F \qquad \text{(inhalation)}$$

$$+ \left[f_a \cdot M_\ell \cdot v_d \cdot K_r \cdot 10^6\right] \cdot F \qquad \text{(resuspension)} \qquad (16)$$

where

$$C_{k\ell}^T = \text{average toxicological concentration of soluble DU in air to which a person in population class k is exposed during averaging period } \ell \; (mg/m^3)$$

$$10^6 = \text{conversion factor } (mg/kg)$$

and all other variables are as defined in Equation 14. It is important to note that for acute exposures (i.e., less than 1 work week), toxicological concentrations are averaged over the actual duration of exposure. The use of weekly or annual averaging periods are applicable for chronic exposures only.

Exposure to Inhaled Uranium - A second chemical toxicity measure for estimating exposures to airborne concentrations of depleted uranium, the weekly exposure to soluble uranium, is applicable to chronic occupational exposures only (Reference 5). However, this measure can be shown to be equivalent to the average concentration measure in Equation 16.

D. SUMMARY OF FIXED PARAMETER VALUES

Table 8 summarizes the values and sources for all parameters in Equations 14, 15, and 16 that are fixed from scenario to scenario. Values for normalized concentration factors (F) are determined using the analytic procedures described in Section I. Values for all other parameters assume chronic exposure and depend on the specific case being analyzed. When evaluating acute exposures, parameter values should be adjusted accordingly.

TABLE 8
FIXED PARAMETER VALUES FOR CALCULATING CHRONIC EXPOSURE

T-3757a

PARAMETER	RADIONUCLIDE, i	ORGAN, i	POPULATION CLASS, k	AVERAGING PERIOD, ℓ	VALUE	UNITS	SOURCE
Breathing rate, B_k			1-Occupational		3.48×10^{-4}	m^3/sec	Reference 19
			2-General Populace		2.32×10^{-4}		
Source term, A_i	$1-^{234}U$				2.24×10^{-5}	Ci/kg	Product of data in columns 4 and 5, Table 2, Section I, unless specified otherwise
	$2-^{235}U$				5.35×10^{-6}		
	$3-^{238}U$				3.32×10^{-4}		
Deposition Velocity, v_d					10^{-2}	m/sec	Reference 7
Duration of exposure to concentrations, $T_{kℓ}$			1-Occupational	1-Annual	6.91×10^6	sec	Assumed: 240 8-hour workdays
				2-Quarterly	1.79×10^6		62 8-hour workdays
				3-Weekly	1.44×10^5		5 8-hour workdays
			2-General Populace	1-Annual	3.15×10^7		365 24-hour days
Dose commitment factor for internal exposure (chronic or acute) to air concentrations, DFI_{ij}	$1-234U$	1-Whole Body			6.46×10^5	$\frac{rem}{Ci}$	Reference 21
		2-Critical Organ (Lungs)			5.22×10^7		
	$2-235U$	1-Whole Body			6.07×10^5		
		2-Critical Organ (Lungs)			4.90×10^7		
	$3-238U$	1-Whole Body			5.67×10^5		
		2-Critical Organ (Lungs)			4.58×10^7		
Dose commitment factor for chronic external exposure to ground concentrations, DFD_{ij}	$1-234U$	1-Whole Body			2.03×10^{-6}	$\frac{rem/sec}{Ci/m^2}$	Reference 21
		2-Critical Organ (Lungs)			2.03×10^{-6}		
	$2-235U$	1-Whole Body			3.65×10^{-4}		
		2-Critical Organ (Lungs)			3.65×10^{-4}		
	$3-238U$	1-Whole Body			9.77×10^{-4}		
		2-Critical Organ (Lungs)			9.77×10^{-5}		

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SECTION III
LIMITS FOR EXPOSURE TO DEPLETED URANIUM

In this section recommended limits for chronic expo-
sure to depleted uranium are discussed. The following indices
are considered for both occupational and general populace ex-
posures:

- Whole-body dose

- Critical-organ dose

- Radiological concentrations of DU in air

- Toxicological concentrations of soluble
  DU in air.

Sections III,A and III,B present the limits against which the
computed radiological and toxicological exposure measures are
compared to assess compliance with recommended guidelines.
These maximum exposure limits have been described according to
procedures and criteria outlined by the U.S. Nuclear Regula-
tory Commission (10 CFR 20) (Reference 5) and the International
Commission on Radiological Protection (Reference 19). A summary
table appears in Section III,C.

A. LIMITS FOR RADIATION DOSE

1. Whole-Body Limits

10 CFR 20 sets the following occupational and general
populace limits for whole-body dose:

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- 5 rems/yr for occupational exposures

- 0.5 rems/yr for general populace exposures.

These limits are applicable for both soluble and insoluble uranium compounds. The general populace limit is lower because of the potential presence of children in the group (Reference 19).

Maximum exposures of 5 rems/yr to a worker may be exceeded only if (1) the dose received in any one calendar quarter does not exceed 3 rems and (2) the dose to the whole body, when added to the accumulated occupational dose to the whole body, does not exceed $5(N-18)$ rems, where N is the individual's age in years at his last birthday. Therefore, the 5 rems/yr value may be viewed as a conservative limit.[*]

2. Critical-Organ Limits

The following body organs receive dose commitments from both internal and external exposure to the isotopes in depleted uranium, and are considered the organs most likely to be critical (Section III,B,1). Recommended annual occupational radiation limits for these organs are also given (Reference 19).

Organ	Annual Occupational Dose Limit (rem)
Bone	30
Kidney	15
Lungs	15
GI-Lower Large Intestine	15

[*] In keeping with the spirit of 10 CFR 20, every effort should be made to maintain levels of radiation exposure "as low as reasonably achievable" (ALARA).

The critical organ for insoluble DU compounds is the lungs; the recommended occupational limit for this organ is 15 rems/yr. When the DU compounds are soluble in body fluids, the critical organ, from the standpoint of radiological damage, will be an organ other than the lungs (see Section II,B,2). However, since the occupational limit of 15 rems/yr is the most stringent of the organ limits specified above, this measure is applicable for both insoluble and soluble compounds of uranium.

In deriving annual general populace exposure limits for the critical organ, one must again allow for the potential presence of children in the population. Accordingly, the occupational radiation limit for the critical organ should be reduced by approximately a factor of 10 to determine the general populace value (Reference 19). This results in a general populace limit of 1.5 rems/yr for the critical organ, which is relevant for both insoluble and soluble forms of uranium.

B. LIMITS FOR EXPOSURE TO CONCENTRATIONS OF DU IN AIR

1. Radiological Concentration Limits

For the purpose of limiting the exposure of individuals to concentrations of radioactive materials in air, maximum permissible concentrations (MPC_a's) are established by isotope (soluble or insoluble) for both workers and members of the general populace in 10 CFR 20. The occupational MPC_a is defined as an average concentration which, if inhaled uniformly for 40 hrs/week, 50 weeks/yr, for a continuous work period of 50 years, will impart the maximum allowable radiological dose to the critical organ of an individual (Reference 19). MPC_a's for the general populace, are derived assuming 50 years of continuous exposure (168 hrs/week) and allowing for the potential

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presence of children in the group; resulting exposure limits are about a factor of 30 lower than the occupational MPC_a's (Reference 19). For the purpose of comparison against the prescribed MPC_a's, radiological concentrations are averaged quarterly for occupational exposures and annually for general populace exposures (Section II,C,1).

Using the isotopic composition of DU and the MPC_a for each uranium isotope, the maximum allowable radiological concentration for the DU mixture as a whole can be computed. 10 CFR 20 requires that the following condition be met:

$$C^R \cdot \sum_i \frac{f_i}{MPC_i} \leq 1 \qquad (17)$$

where

i = index of a uranium isotope

C^R = average radiological concentration of the DU mixture in air ($\mu Ci/m\ell$*)

f_i = the number of curies of isotope i per curie of DU[†] (values are 0.062 for ^{234}U, 0.015 for ^{235}U, and 0.923 for ^{238}U)

MPC_i = the maximum permissible radiological concentration of isotope i in air, as specified in Reference 5 (Tables I and II) for insoluble or soluble compounds ($\mu Ci/m\ell$*).

Using Equation 17, the maximum permissible radiological concentration for the DU mixture (C^R_{max}) is determined as follows:

---

*Note: 1 $\mu Ci/m\ell$ = 1 Ci/m^3.

[†] $f_i = \dfrac{\text{weight fraction} \times \text{specific activity of isotope } i}{\text{specific activity of DU}}$

$$C_{max}^R = \frac{1}{\sum\limits_{i} \frac{f_i}{MPC_i}} \qquad (18)$$

Occupational and general populace values of $\bar{\chi}_{max}$ for both soluble and insoluble DU compounds are given in Table 9.

It is important to note that <u>the use of MPC$_a$ standards alone is only valid if there are no significant contributions from external sources of radiation</u> (Reference 19). For cases where external radiation exists, the following approach is taken:

- Whole-body and critical-organ doses from both internal and external sources are computed according to the procedures described in Section II,B and compared against the appropriate dose limits in Section III,A

- The MPC$_a$'s are reduced by the amount of the external radiation dose before these values are compared against the computed radiological concentrations in air. That is, C_{max}^R in Equation 18 is adjusted as follows for occupational and general populace exposures:

$$(C_{max}^R)_{adjusted} = (C_{max}^R) \times \left(1 - \frac{\text{annual external dose to the critical organ}}{\text{annual dose limit for the critical organ}}\right) \quad (19)$$

2. Toxicological Concentration Limits

When low-level radioactive compounds of uranium are soluble, chemical toxicity in the body becomes a greater limiting factor than radioactivity. Consequently, measures have

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been provided in Appendix B of 10 CFR 20 for limiting the con-
centration of soluble uranium in air such that the maximum
permissible toxicity burden to the critical organ (kidney) is
not exceeded. For soluble mixtures of uranium isotopes, if
the percent by weight of ^{235}U is less than 5%, the average
permissible concentration of uranium in the air breathed may
not exceed:

- 0.2 mg/m^3/work week for occupational
  exposures

- 0.007 mg/m^3/year for general populace
  exposures.

It is important to note that these prescribed standards
were established on the basis of <u>chronic</u> exposures. For acute
exposures (i.e., less than 1 work week) to concentrations of
soluble uranium in air, the average concentration limit should
be adjusted to reflect the actual duration of release to provide
a more equitable measure by which to compre the calculated
toxicological concentration in air.[*] The use of concentration
limits derived for chronic releases is a conservative standard
by which to assess compliance for an acute release.

C. SUMMARY OF EXPOSURE LIMITS

Table 9 summarizes all chronic exposure limits dis-
cussed in this section.

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[*]To date, 10 CFR 20 acknowledges the need to adjust chronic
  limits for compatibility with acute releases, but does not
  indicate specific procedures for doing this.

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TABLE 9
SUMMARY OF CHRONIC EXPOSURE LIMITS

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EXPOSURE INDEX	OCCUPATIONAL LIMITS			GENERAL POPULACE LIMITS		
	UNITS	INSOLUBLE DU	SOLUBLE DU	UNITS	INSOLUBLE DU	SOLUBLE DU
Whole-Body Dose	rems/year	5	5	rems/year	0.5	0.5
Critical-Organ Dose	rems/year	15	15	rems/year	1.5	1.5
Radiological Concentration of DU in Air	µCi/mℓ (averaged quarterly)	1×10^{-10}	7.5×10^{-11}	µCi/mℓ (averaged annually)	4.9×10^{-12}	3.2×10^{-12}
Toxicological Concentration of Soluble DU in Air	mg/m^3 (averaged weekly)	-	0.2	mg/m^3 (averaged annually)	-	0.007

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